Annual Report

2017

A research group of the Department of Civil and Environmental Engineering at the University of Massachusetts, Amherst
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I am delighted to share with you our 2017 Annual report. Over the past year, the Hydrosystems Research Group (HRG) has worked on diverse projects across the globe to improve the water security of communities and has continued to pursue and publish cutting-edge research in the fields of hydrology and water management. We’ve participated in and presented at Stockholm Water Week, World Bank Water Week, HydroAfrica in Marrakesh, Morocco, the AGU Fall Meeting and ASCE EWRI Congress. We also conducted climate risk assessment training in Korea, Mexico and Amherst with our partners at the World Bank.

We’re thrilled to be continuing our collaboration with the Rockefeller Foundation and the World Bank, which is bringing advanced analysis tools to design investments for resilience to the deep uncertainty that characterizes the future. We continue to work with close collaborators in Mexico City and Tanzania. This year we also launched a new effort with San Francisco Water and the Water Research Foundation on a long-term vulnerability assessment.

In all of our endeavors, our overarching goal is to provide research services and insights that benefit society. The scientific goal of our group is to understand and model complex human-hydrologic systems to improve societal responses to water resources challenges. Most important is the recognition that our research accomplishments are meaningful and impactful when they are co-developed with our partners, and when addressing the practical issues of the here and now.

We thank all of you for your support in our activities and look forward to working together in an exciting 2018!

Dr. Casey Brown
In the past year, members of the Hydrosystems Research Group led and participated in a series of events across the globe. These activities served to promote the group’s research capabilities, disseminate research outputs, acquire skills, grow/establish networks and build capacity of stakeholders.

**December 2016**

**AGU Fall Meeting (San Francisco, California)**

Four members of the Hydrosystems Research Group participated in the 2016 Fall Meeting of the American Geophysical Union in San Francisco. There were two oral presentations (by Hassaan Khan and Katherine Schlef) and two poster presentations (by Dr. Sungwook Wi and Dr. Umit Taner).

**January 2017**

**CUAHSI-NASA Remote Sensing Workshop (Cambridge, Massachusetts)**

Chinedum Eluwa and Hassaan Khan attended a two-day workshop on Remote Sensing for Hydrology. The workshop was hosted by the CUAHSI and facilitated by hydrologists at the NASA JPL. They developed skills in querying databases of remotely sensed data and learnt methods to analyze these data at scale.

**February 2017**

**Resilience by Design Inception Meeting (Mexico City, Mexico)**

Group members (Dr. Casey Brown and Sarah Freeman) on the Freshwater Resilience Team completed an inception meeting with partners on the Freshwater Resilience Team from Mexico City. This meeting provided an opportunity for the research group to learn stakeholders’ concerns and setup a partnership to address these concerns.

**March 2017**

**Africa Hydropower Conference (Marrakesh, Morocco)**

Dr. Casey Brown and Dr. Patrick Ray conducted a training session for about 30 water managers and decision makers at the Africa Hydropower Conference. The session focused on the Decision Tree Framework for Climate Risk Assessment for Water Infrastructure. Alec Bernstein attended and participated in the training session.
April 2017

**Decision Tree Training Workshop (Amherst, Massachusetts)**
The Hydrosystems Research Group in collaboration with the World Bank hosted a week-long workshop for water managers from developing countries on the *Decision Tree Framework*. The workshop sessions touched on all aspects of the framework including model building, system stress testing and resilience components. The training was conducted by group members Casey Brown, Katherine Schlef, Alec Bernstein and David Rheinheimer.

**European Geophysical Union (EGU) General Assembly (Vienna, Austria)**
Baptiste Francois convened a session during the *European Geophysical Union General Assembly* on the modeling and management issues facing hydropower and other renewable sources of energy.

May 2017

**International Joint Commission (IJC) Annual Board Meeting (Washington DC, US)**
Dr. Casey Brown and Alec Bernstein held a workshop during the IJC’s semi-annual board meeting to present the Climate Change Guidance Framework and meet with watershed Board members to discuss the implementation of the framework across basins through a Pilot Study. The framework was developed by the Hydrosystems Research Group and completely carried out by the group in the St. Croix Basin. Other Boards were introduced to the first step of the framework through the Pilot Study.

June 2017

**Progress Meeting (Palisades, New York)**
Katherine Schelf met with partners of the Hydrosystems Research Group at the International Research Institute for Climate and Society. She presented updates and led conversations on her ongoing research on credible flood projections.

**NCAR Conference (Boulder, Colorado)**

**Freshwater Resilience Partners Meeting and Lerma-Chapala Workshop (Mexico City, Mexico)**
The Hydrosystems Research Group met with partners from the World Bank, SACMEX (Sistema de Aguas de la Ciudad de Mexico), CONAGUA and UNAM as part of a workshop for collaborative management of the Lerma-Chapala basin. Dr. Casey Brown, Sarah Freeman and Alec Bernstein presented ongoing work and led discussions with water managers and basin stakeholders.
August 2017

**SCRM Network Climate Risk Management Summer School**
*(State College, Pennsylvania)*

Chinedum Eluwa participated in a summer school hosted by the SCRM Network. The summer school covered interdisciplinary approaches in dealing with climate risk management. Topics included communications methods, policy development, integrated assessment modelling and robust decision-making techniques.

**World Water Week (Stockholm, Sweden)**

Dr. Casey Brown and Sarah Freeman attended the World Water Week in Stockholm. They presented ongoing work on Freshwater Resilience with partners from the World Bank and Rockefeller Foundation.

September 2017

**Freshwater Resilience Partners Scoping Meeting (Tanzania)**

Dr. Casey Brown and Alec Bernstein travelled with the World Bank on a scoping mission to Dar es Salaam, Dodoma, Iringa and Morogoro, Tanzania. They presented the Freshwater by Design methodology to various government ministries and basin stakeholders. The scoping mission was the first to kick off the Freshwater Resilience by Design work in Tanzania, and the members learned about pressing issues facing river basins from the local river basin board members.

November 2017

**Lerma Basin Scoping Meeting (Mexico)**

Members of the Hydrosystems Group, met with stakeholders within the Lerma Basin from November. The Group conducted a successful inception meeting with Lerma Basin stakeholders and also held a technical workshop and reported on the ongoing modeling work for the Basin. The members of the group who attended were Casey Brown, Sarah Freeman and Sungwook Wi.

December 2017

**Hydrologic Risk in Hydropower Dominated Energy Systems Workshop**

Alec Bernstein travelled an International Hydropower Association (IHA), World Bank and Nordic Development Bank funded workshop on assessing and mitigating hydrologic risk in hydropower dominated energy systems in London, UK. The workshop’s geographic focus was Africa and provided an opportunity to learn from private practitioners of hydropower insurance.
and risk within the African context. Alec presented the Freshwater Resilience by Design methodology and bottom-up climate risk assessment framework for the Batoka Gorge Hydropower Scheme study.

**American Geophysical Union Fall Meeting (New Orleans)**

Ten HRG members attended the 2017 Fall Meeting of the AGThe Hydrosystems Research Group had a good outing at the annual Fall meeting of the American Geophysical Union. 9 members of the group (Sungwook Wi, David Rheinheimer, Hassaan Khan, Umit Taner, Katherin Schlef, Baptiste Francois, Sarah Freeman, Chinedum Eluwa) made either presentations or posters and Casey Brown played a key role in organizing the Hydrology section of the conference.
Project Summaries

Over the past year, the Hydrosystems Research Group (HRG) has worked on diverse projects across the globe to improve the water security of communities and has continued to pursue and publish cutting-edge research in the fields of hydrology and water management.

The overall goal of our group is to understand and model complex human-hydrologic systems to improve societal responses to water resources challenges. Human-hydrologic systems are particularly vulnerable to climate variability and climate change and we focus on climate risk assessment and management. Our work will provide insight for planning and adapting the design and management of resilient water resource systems for a sustainable future.

Climate Stress Test in a nutshell

At its core, climate stress test is a bottom-up, exploratory modeling technique to understand how a system responds to changes in climate and discover future conditions that could lead to unacceptable or negative consequences in the underlying water resources system. A climate stress test involves four major steps:

The first step is to establish performance indicators and critical thresholds related to the water resources system to describe undesired consequences, for example, a water system reliability of below 95%. These performance indicators and thresholds are generally defined with the project stakeholders.

The second step to explore a wide range of future climate conditions that may occur in the future and assess the water resources system performance across these conditions using simulation models. Plausible future climate conditions can be obtained from a weather generator to produce numerous stochastic time series that preserve the variability and seasonal and spatial correlations of the historical climate record. Plausible climate change effects are then reflected on the stochastic time series by systematically varying selected statistical properties of climate variables such as average amount, frequency or duration.

The third step is to summarize the findings of the exploratory modeling analysis and depict the vulnerabilities identified such as violations of performance thresholds. This can be done through climate response maps that directly relate performance indicators to future conditions such as changes in mean temperature and precipitation.

The fourth step is to determine the plausibility of the problematic climate changes resulting vulnerabilities. This is done by making use of best-available information from various sources such as downscaled climate model projections, paleoclimate data or expert judgments. These sources of information can be combined with climate response maps to visualize the range of risks in the water resources system under climate uncertainty.
The Valley of Mexico is home to Mexico City (MCMA), one of the world’s largest urban conglomerates with a total of 20 million inhabitants in its metropolitan zone. The water system that serves the city is highly complex with diverse and rapidly evolving demands and an intricate institutional network that underpins it all.

At present, 39% of Mexico City’s water supply is sourced from the Cutzamala and Lerma Systems which are located west of the city in the Valley of Mexico. This water is transferred to the MCMA at considerable cost and with, at times, complex politics. The remaining 61% of the supply is extracted from an already overexploited aquifer leading to continued subsidence of the city at rates that range from 4 to 24 cm annually. A trend analysis conducted by Mexico City’s water utility, SACMEX, estimated that if current patterns continue unfettered, the percent of the population receiving reliable water services will be decrease from 82% to 28% by 2025.

The HRG, in partnership with the World Bank, the Rockefeller Foundation and government counterparts in Mexico, are implementing the Freshwater Resilience by Design methodology to identify and prioritize interventions that can help to alleviate the current stresses on the water system in Mexico City and the surrounding Valley of Mexico and to build its resilience to the uncertainties and surprises of the future.

**Approach**

A modular approach of the *Freshwater Resilience by Design* process is being adopted in order to model the full water supply system of the Valley of Mexico. The full systems may be subdivided into three major components: the Cutzamala System, the Lerma System, and Mexico City (CDMX). In this instance, the first two steps of the process (i.e. definition of analysis scope and intervention opportunities...
and collaborative modelling) for each of the three component models will be undertaken separately. At the end of the second step, the three component water systems models will be joined in order to undertake the third and fourth steps of the process (i.e. Identify optimal intervention portfolios and data visualization and intervention road map) for the Valley of Mexico Water System as a whole. The *Freshwater Resilience by Design* process for the Valley of Mexico as well as progress to date is depicted below.

Due to the complex nature of the water supply system in the Valley of Mexico, a modular approach is being taken to develop the Cutzamala, Lerma, and Mexico City models. The Cutzamala coupled systems and hydrological model (CutzSim), which was the first module to be undertaken, was completed in the Summer of 2017. The Lerma and Mexico City (LermSim and SimCDM, respectively) are currently under development and are expected to be completed in the summer of 2018. These three models will then be integrated with a meta-model in the fall of 2018.
Initial Results: Resilience in the Cutzamala Water System

The Cutzamala water system is located west of Mexico City and represents a complex inter-basin water transfer to the MCMA involving reservoirs (mainly the dam reservoirs forming seven sub-catchments, pumping stations (overcoming more than 1,100 meters of elevation difference), open channels, tunnels, pipelines and aqueducts. The CWS was constructed between the late 1970s and early 1990s, and now supplies 20 to 25% of the freshwater used by the MCMA. Figures on this page show the CWS and a schematic of the model used.

The overarching goal for the CWS is to reliably supply water to the nation’s capital, while respecting the water rights of inhabitants of the catchment areas. The evaluation conducted by the HRG is intended to evaluate how potential investments and changes in the operational rules of the system can help the system achieve its operational goals into the future.
First, the performance of the current system under multiple climate futures (i.e., a climate stress test) was evaluated in order to identify system vulnerabilities to changes in climate. The Climate Stress Test shows the result of this climate change stress test of the current system under current operating rules. In this figure, the contours represent maximum reliable yield of the system and the black line represents the current delivery target (495 MCM annually). Critically, this figure also shows us that the maximum reliable yield of current system under current climate conditions is 469 MCM and that the majority of climate projections for 2050 will result in further reductions in this maximum reliable yield.
Next, the relative merits of selected investments that might improve the system’s resilience were assessed, shown in the Table on this page. The results of the evaluation of investment combinations (64 total) under optimized operating rules which are derived from maximizing reliable yield and resilience of the system are shown below. The results indicate the proposed development of Temascaltepec reservoir is the best option for increasing the maximum reliable yield, robustness and resilience of the system. However, it is the most costly and controversial. Following the initial completion of the analysis an additional investment (the Villa Victoria Pressurized Canal) was introduced and modeled. The
new consideration of Villa Victoria Pressurized Tunnel in conjunction with an expansion of the reservoirs current capacity yields improvements in all performance metrics considered. With additional storage capacity, this option becomes the best performing investment that does not include Temascaltepec. This option is also less costly than the previously best performing investment portfolio which did not included Temascaltepec. This option increases the maximum reliable yield of the CWS to 562 MCM which represents about a 20% increase from the current systems and falls just short of the approximate 22% increase which would be provided by an investment in Temascaltepec. The robustness of this option is also the highest of the option portfolios which does not include Temascaltepec. Regarding average recovery time after failure of the CWS to deliver water to MCMA, this investment decreases the average recovery time from about 10 days (the current system without reoperation of reservoirs) to about 1 day.

Parallel Coordinates plot showing the Performance of the new investments related to the Villa Victoria pressurized tunnel relative to all previously evaluated investment combinations. For reference, the previously best performing portfolio without Temascaltepec (Portfolio A) is also highlighted.
The evaluation of this new investment in the Villa Victoria Pressurized Canal and expansion of the Villa Victoria reservoir has been a milestone for the *Freshwater Resilience by Design Process* in the Cutzamala system as it clearly demonstrates the benefit of increased connectivity in the CWS, shown below.

**Upcoming Milestones**

The HRG is currently expanding the models that will be included in the final evaluation. This year will focus heavily on stakeholder engagement to and modeling efforts for the Lerma system as well as Mexico City itself. In this effort, the HRG is working closely with fellow experts at the University of Cincinnati and National University of Mexico.

The project is ongoing and is expected to be completed by September 2018.
World Bank Water Security Diagnostic

The Hydrosystems Research Group is collaborating with the World Bank to develop a Water Security Diagnostic tool. The Water Security Diagnostic is a systematic process to identify water-related risks and opportunities, to determine factors that support or compromise water security and to provide strategic recommendations on priority areas for investments. The process focuses on a structured and repeatable assessment. The assessment will be conducted as a collaborative process with a local World Bank country team in consultation with country counterparts, local stakeholders and local and global experts.

Members of the Hydrosystems Research Group are working with Bank staff to draft the Diagnostic and are implementing resilience thinking into the text of the document. The HRG is involved in the structure of the Diagnostic and the implementation phases.

The Diagnostic is divided into five steps, outlined here:

**Phase I – Define Scope.** The objective of this phase is to identify the scope of the diagnostic assessment, including the development objective, geographic focus and resources available to complete the assessment. The outputs of this step are a clear understanding of the scope of the assessment, which actors and stakeholders should be involved in the preparation of the diagnostic, and a detailed Terms of Reference for consultants who will be engaged in the process.

**Phase II – Establish Context.** This phase has the objective of establishing the context and describe the most relevant macro-trends in the study area. A complete review of the social, economic and environmental characteristics of the study area is performed using existing data and information. Particular attention to mega-trends in the study area and how they are
expected to affect water-related outcomes. In this phase, a review is completed of previous World Bank engagements, especially those with respect to water sector investments. Past lending and knowledge activities in the country are relevant to diagnosing issues and identifying potential investment opportunities. The final component of this phase involves a description of the mega-trends and their influence on water related outcomes, in general and quantitative terms.

Phase III – Examine Outcomes This phase has two objectives: (i) determine to what extent water related factors constitute a risk to society, the economy and the environment, and (ii) determine if and to what extent water related factors provide opportunities for development. This phase is split into three steps. Step 1 constitutes a review of the outcomes of the actions of water security across three areas: society, the economy and the environment. Step 2 benchmark’s the study area against “peers” of the same scale (country, basin, city). This benchmarking is intended to compare or measure specific water related outcomes from the study area to a standard based on regional or global averages. Step 3 involves developing a narrative on the social, economic and environmental outcomes related to water supported by data and benchmarking. This produces a detailed assessment of the status and trends of the outcomes related to water that highlight the key areas for detailed diagnostic.

Phase IV – Diagnose actions of Water Security. The objective is to assess the actions of water security that give rise to the outcomes in Phase III. Actions of water security are divided into management of water resources, delivery of water services and mitigation of water related risks. Actions in each category are diagnosed asking the following questions:

- To what extent are water resources being managed sustainably, efficiently and equitably?
- To what extent are water services being delivered inclusively, reliably and affordably?
- To what extent are water related risks being recognized and mitigated to enhance resilience in an inclusive manner?

The outputs from this phase is an understanding and description of the extent to which actions are determining outcomes, especially those of most concern.

Phase V – Diagnose Capitals of Water Security. Assess the capitals supporting or constraining the actions of water security. This phase combines insights from Phase III and IV to link the actions of water security to the capitals of water security. This amounts to describing why the actions are effective or not in determining positive water-related outcomes. In this phase, the natural capital, infrastructure and financial capital, human capital, information support, and political economy factors are assessed to whether each supports or constrains water security. The output of this phase is the diagnostic assessment which describes where aspects of the capitals of water security that constrain action or need to be augmented. This outcome describes which capitals of water security are supporting or
constraining progress toward water security and informs strategic recommendations of priority areas for investment and future program design.

The output of the Diagnostic process is a full report combining written material with geospatial information to provide a geographically explicit representation of findings where appropriate. The Diagnostic assessment answers two main questions: (i) what are the social, economic and environmental water-related outcomes of greatest concern? (ii) which foundational capitals of water security constrain or support the actions that determine these outcomes?

A framework for water security diagnostics, structured into three level and showing how outcomes are the combined result of the capital and actions of water security.
Overview

The Hydrosystems Research Group conducted a Pilot Study to fully implement the International Joint Commission’s (IJC) “Climate Change Guidance Framework” in the St. Croix River Board and introduced the first step with all other Boards across the continent. The IJC is a transboundary organization between Canada and the United States to prevent and solve disputes related to water resources and pursue the common good of both countries as an independent and objective advisor to the two governments.

The Climate Change Guidance Framework is used to assist IJC Boards address climate change within the bounds of their mandates. The framework guides the Boards to analyze and act on climate change issues in a logical manner. The Framework consists of four primary steps:

1. **Organize** – In the **organize** step, each Board formulates its climate change related objectives and assesses what information is available and what is needed to prepare to meet those objectives successfully. The goal of this step is for the Board to do a self-analysis with a clear, complete understanding of the objectives that the Board is trying to achieve.

2. **Analyze** – The **analyze** step has the Board produce quantified estimates of how a change in climate might produce different outcomes for their activities. The Board prioritizes the most critical, and evaluates the likelihood of the outcomes. This step involves analysis to quantify the effects of climate change on Board activities. The analysis will estimate how a change in climate may produce different outcomes for Boards.

3. **Act** – In the third step, **act**, the Board uses the tools and networks to quantify the problem to evaluate different responses and based on this, the Board makes decisions that it believes would improve their response. The step formulate a plan of alternative actions the Board can undertake to address the concerns identified in the previous steps.

4. **Update** – The final step, **update**, is adaptive management or the establishment of a process to improve the Board’s “act” decisions based on a formalized, ongoing effort to systematically assess the Board’s challenges over time. A simple adaptive management plan would be to revisit the discussion every five years, passively reviewing information
developed by others, and complete a short review to ask whether there is any reason to go through the steps again.

The HRG introduced the pilot study to Boards at the IJC Semi-Annual meeting on May 4th in Washington, DC. The steps of the Climate Change Guidance Framework were presented, and the Boards, with the guidance of the HRG and other consultants, had a discussion on climate change adaptation pathways. The pilot project involved two components: (i) introducing the first step of the four step guidance framework (Horizontal Roll Out) across control, watershed, and pilot watershed Boards and (ii) introducing the entire four step framework (Vertical Roll Out) to the International St. Croix Watershed Board.

**Horizontal Roll Out**

The “Horizontal Roll Out” of the pilot involved an assessment of each Board’s missions and objectives that could be impacted by climate change and what information the Board already has, or needs, to prepare for and minimize risks associated with climate change. The goal of the Horizontal Roll Out is to provide clear guidance to the Boards for addressing climate change in IJC policy and operations using the best available institutional and organizational science and stakeholder inputs available to the Boards. The Boards included in the “Horizontal Roll Out” study include:

- Accredited Officers for the St. Mary – Milk Rivers,
- Columbia River Board of Control,
- Kootenay Lake Board of Control,
- Lake Ontario – St. Lawrence Board,
- Lake Superior Board of Control,
- Niagara Board of Control,
- Osoyoos Board of Control,
- Rainy-Lake of the Woods Watershed Board,
- Red River Board,
- Souris River Board

**Vertical Roll Out**

The “Vertical Roll Out” was performed in the St. Croix River basin. The St. Croix River is a transboundary river along the Canada and United States border between New Brunswick and Maine on the eastern end of the continent. The river is 110 miles (185 km) long and drains an area of 1,642 square miles (4,271 km²). The river is in a unique location and comprises the easternmost land border between the two countries. There are two principal chains of lakes in the watershed’s headwaters. The eastern chain of lakes follows the mainstem of the St. Croix River and includes two of the largest lakes in Maine and New Brunswick: Spednic and East Grand Lake. The Eastern branch of the St. Croix forms the international border.
The “Vertical Roll Out” analysis provides a bottom-up assessment of climate change vulnerabilities in the St. Croix watershed associated with violating the Board’s specific performance targets. The method focuses on identifying stakeholder-defined vulnerabilities in a given environmental resources system to climate uncertainty, rather than focusing on predictions of future climate that are subject to various climate modeling and downscaling approaches. This is typically done by considering a broad range of plausible futures, and then explore vulnerabilities across those futures using computationally inexpensive simulation models. Identified vulnerabilities are then linked to climate information obtained from climate models or experts for aiding the decision-making processes.

The bottom-up climate vulnerability analysis approach adopted to the St. Croix Watershed pilot study consists of four phases:

1. Definition of objectives and critical thresholds related to the minimum flows and lake levels at various points in the basin,
2. Developing a coupled hydrology-water system model at the appropriate scale to analyze system performance under different conditions,
3. Implementation of climate stress test, to assess the violations related to the previously defined critical thresholds across a broad range of plausible climates, and
4. Identifying climate-informed risks by linking climate stress test outcomes to the outputs of Global Circulation Model (GCMs).

The International St. Croix River Watershed Board’s main objective is to maintain appropriate flows and levels at several key locations within the basin, based upon the St. Croix River Orders of Approval. Climate change is predicted to influence the climatology and hydrology of the St. Croix Basin. The question is, how might that affect the ability to meet the Board’s objectives? All of the GCM models predict some warming to occur by 2050, from 0.2°C to over 4°C.

Droughts are expected to become more intense in the future. Drier periods may last longer in the future, impacting the hydrology of the basin. As temperature rises, more precipitation will fall as rain and the declining snowpack will affect the timing of runoff.

The HRG utilized a hydrologic-systems model to explore the vulnerabilities associated with violating the Board’s specific performance targets. The stress test is performed by first generating a wide range of future climate conditions, and then simulating the system response (i.e., the physical hydrology and water system operations to those climate conditions).

The HRG performed a climate informed risk analysis, where the
results from the climate stress test were evaluated with the GCM projections to identify the future conditions of the greatest concern.

**Modeling Results**

The climate response surface (see the figure below) shows the range of minimum flow violations in the watershed across a plausible range of climate changes, i.e., changes in mean temperature up to 5 °C and changes in annual mean precipitation from -20% to 30%. Results indicate that the number of violations can be as high as 60 per year under very dry (-20% decrease in precipitation) and very warm (5 °C increase in temperature) future conditions. However, violations are less than 5 times per year in the GCM-projected range of climate changes, which are superimposed over the climate response surface.

Overall, the analysis shows that the total frequency of lake level violations is highly sensitive to changes in the annual mean precipitation, and range from zero to more than 10 violations per year. The frequency of violations is up to 5 violations per year under a precipitation change of -20%, and up to 12 violations per year under a precipitation increase of 30%. However, the total frequency of lake level violations in the GCM-projected range is less than 5 violations per year. The total frequency of minimum flow violations can be as high as 50 times per year under the driest (-20% change in precipitation) and the warmest (+5 °C) future. However, based on the current set of GCM projections, these future changes are less likely to occur. The frequency of violations in the GCM-projected range ranges from about 0 to 5 violations per year.

The Pilot Study was well received by the IJC Commissioners, and the Hydrosystems Research Group will present the results of the Pilot Study to the Commissioners and Boards at the next Spring Semi-Annual Meeting.
OpenAgua: A Web-Based Application for Modeling Water Systems for Water Resources Planning and Management

Overview

Water system models are often at the core of a systems analysis approach undertaken by the Hydrosystems Research Group to understanding water systems under uncertainty, and are widely used to inform water planning. However, system models have historically been developed on desktop computers by individual specialists, who act as gatekeepers to the system model and its data and results. While some existing applications (e.g., WEAP, RiverWare, AquaTool, etc.) make water system modeling easier—and accessible to the non-coder—their confinement to computer desktops limit 1) their potential in a distributed decision-making environment and 2) their computational complexity, which may be limited by a computer’s processing power.

Modern web technologies help ameliorate these issues. While accessible online communication has existed for well over two decades now, only recently have web application (web app) frameworks become sufficiently advanced to enable development of fast, good-looking, highly interactive web apps, as we see in, for example, Google Docs. Furthermore, cloud computing services enable easy access to computers far more powerful than what may be immediately accessible to a modeler.

Objectives

OpenAgua (www.openagua.org) aims to be a one-stop web application for collaborative water systems modeling using the best of these recent innovations in web technologies. Specifically, with OpenAgua the Hydrosystems Research Group seeks to help deliver on the promise of the web to facilitate collaboration in all facets of water systems modeling, including development of the model itself (building a system network, entering data, designing “stress tests”, etc.), running a built-in or user-supplied model, developing management options and portfolios, integrating
climate and other stressor scenarios, and exploring model results. Importantly, we envision a direct connection between the model & data and stakeholders, via stakeholder-centric interfaces, to allow stakeholders to interact with the model & data directly, not necessarily facilitated by an intermediary modeling expert. While OpenAgua will include a range of control and visualization tools out-of-the-box, it will also enable development of new interaction tools that can be developed in collaboration with stakeholders.

In the context of on-going efforts in the Hydrosystems Research Group, OpenAgua is being developed to address the immediate need of an online, open source graphical interface and model to assess and enhance resiliency of Mexico City’s water system to multiple stressors, and to assess the vulnerability of San Francisco’s water system to climate change.

Summary of Recent Activities

Phase I saw the development of a preliminary prototype, using somewhat older web technologies (e.g., jQuery).

Phase II, now well underway at UMass, comprises of:

1) Replacing the older technologies by newer, more appropriate technologies. Among other improvements, the application is being converted to use the React JavaScript library. Compared to the predecessor library used (jQuery), React results in a faster application (better for application users) and is easier to understand (better for application developers).

2) Developing/refining core features of the platform. These include, among others:
   - A facility to share/control access to water system with other platform users and the public for collaboration and communication (Figure 1).
   - A prototype simplified view of a “public” project outside the core application (Figure 2). This could facilitate communication of modeling efforts and sharing results with collaborators and/or the public.
   - The ability to run a model. Though first achieved in Phase I, this facility now enables:
     i. Running a model using a manually-added cloud computer (using the Amazon Web Services platform)
     ii. Seeing model progress, even after logging out and logging back in.
     iii. Running any arbitrary model developed by the user, not necessarily the demand-driven model packaged with OpenAgua.
Interconnectivity with other web-based services. For example, OpenAgua connects to Google Earth Engine to display global streamlines (from the HydroSHEDS datasets), which can facilitate drawing river networks. (In the future, this will connect with a build-in hydrologic modeling facility).

These core features, though not fully developed, have been developed sufficiently over the past year to demonstrate viability, as shown in the figures below, and continue to be actively developed/refined. In addition, many other features continue to be developed/enhanced.
Overview

The Hydrosystems Research Group is partnering with the San Francisco Public Utilities Commission (SFPUC) to perform a climate risk assessment on its urban water supply. The San Francisco Bay Area obtains water from watersheds distributed across three distinct regions in California, each with a unique topology and hydrology. These regions are referred to as the Upcountry (in the Sierra Nevada), the Alameda and the Peninsula watersheds (west of the Central Valley), shown in the figure below. Almost 85% of water supplied by the SFPUC comes from the Upcountry watershed. Reservoirs in the Alameda watersheds, along with those in the Peninsula, comprise the local storage available to the SFPUC, and therefore have a high strategic importance despite the relatively small percentage (~20%) of total water supplied that they comprise.

Climate change and other changing conditions may jeopardize the future ability of the Upcountry watershed to meet the San Francisco Public Utilities Commission’s (SFPUC) desired level of service. Current planning will benefit from early identification of potential vulnerabilities and evaluation of possible adaptations to address them.
The Hydrosystems Research Group is working with SFPUC to provide the insights needed to plan for an uncertain future by conducting a comprehensive vulnerability assessment of climate and other drivers for change and adaptation planning process. A tailored methodology will be utilized to complete the following tasks:

1. **Identify vulnerabilities** through exhaustive, systematic exploration of uncertainty ranges of future conditions
2. **Assess the risks** associated with these vulnerabilities through integration of the best available climate information
3. Develop and evaluate an **Adaptation Plan** consisting of a portfolio of options that together are flexible and robust to a wide range of futures

### Hydrosystems Group Approach

As has always been the case, future performance of water systems depends on a number of factors that may change in the future. The approach used here provides a comprehensive understanding of system performance over a wide range of possible futures, and in doing so, clearly defines the conditions that cause failure and identifies priorities for adaptation planning. The computational engine of this analysis is a multi-dimensional, algorithmic sensitivity analysis—a stress test—that explores ranges of uncertain variables, including both climate and non-climate uncertainties, and creates a database of system response that is then mined to identify vulnerabilities. The analysis results are not dependent on specific climate projections and all their uncertainties, but climate projections are interrogated to assess a “level of concern” to associate with vulnerabilities that are identified. Likewise, non-climate vulnerabilities are further analyzed to assess the level of risk they present. The execution of this effort depends on functional hydrologic models of reservoir inflows and system models representing reservoir operations, infrastructure connections, water demands, revenue generation, costs and regulatory requirements.

### Phase I – Develop Detailed Workplan

In the first Phase we design and execute an exhaustive vulnerability assessment that provides a comprehensive understanding of the expected water system performance relative to goals and expectations. In doing so it will reveal the specific combination of factors that lead to a failure to meet performance goals, which we define as vulnerabilities. A number of preparatory steps are required to complete the vulnerability assessment.
The first task in this vulnerability assessment was the development of the analysis framework based on clear articulation of the goals of the study, scope of the study and the available resources, including data and modeling tools. To do so, an initial internal kick-off meeting was held at SFPUC headquarters. This 2-day kick off meeting consisted of a workshop with the Water Enterprise Executive Team (WET) of the SFPUC, interviews with senior SFPUC staff and site visits. During the workshop with the WET, a group discussion was held to select long-term sources of vulnerability to include in the study, rank these concerns in order of importance and determine the level of uncertainty associated with each of these vulnerabilities. A source of vulnerability is defined as an uncertain factor or condition that lies outside the control of the Water Enterprise and can significantly disturb the operations of the Regional Water System. The figure below represents the workshop participants’ characterization of uncertainty and importance for each of the sources of vulnerability.

![Scatterplot showing the distribution and importance of, and uncertainty associated with, identified sources of vulnerability](image-url)

There are a few notable high level take-aways from these discussions. The first is the high ranking of natural hazards in terms of both uncertainty and importance. Next are a tier of uncertainties clustered in terms of their uncertainty ranking: climate change, political/legislative, technology, environmental and drinking water regulations, and regionalization. Their assessed importance varies yet based on the discussions and pre-workshop interviews each has the
potential for significant effects on the Water Enterprise performance. These uncertainties have probabilities of occurrence that are not known or easily estimated, unlike earthquakes, and thus are best explored through the methods to be employed in the vulnerability analysis. Finally, there is a wide disparity in the ratings of the degree of importance of almost all uncertain factors, reflecting the range of opinions within the executive team and the difficulty in assessing importance a priori. Indeed, a primary goal of the vulnerability analysis will be to elucidate the importance of these factors through quantitative assessment of their actual effects, allowing an informed prioritization of concerns, and if necessary, adaptive responses.

The figure on this page shows how the identified sources of vulnerability are interconnected. The color of the connecting links between sources refers to the source of influence. For example, the link from Climate Change to Water Demand is red because Climate Change influences Water Demand. The number next to each source of vulnerability refers to the number of drivers influencing it. For example, Financial is influenced by 7 other sources of vulnerability. The most interconnected sources of vulnerability are Financial, Infrastructure and Water Demand. The figure shows that three sources of vulnerability are highly influenced by other factors, Financial (7), Infrastructure (6) and Water Demand (5). These factors will require a dynamic understanding of change over time and therefore, likely need quantitative simulation in the modeling framework. Also, three factors are almost entirely independent but influence other factors, Political/Legislative (6), Climate Change (5), and Natural Hazards (5). These factors are important to include as drivers but can be modeled independently.
Phase II – Conduct Vulnerability Assessment

A vulnerability assessment will be designed and performed to explore the RWS performance under a wide range of uncertainties identified and evaluated in terms of the performance metrics and thresholds specified. The computational engine of the vulnerability assessment is a multi-dimensional, algorithmic sensitivity analysis that links the simulation tools used to represent the system and estimate its performance under changing conditions. This stress test exhaustively and systematically tests the system using Latin hypercube sampling (Stein, 1987) to identify vulnerabilities and link them to the specific factor, or combination of factors that causes them. This combination of factors that constitute a vulnerability is called an “ex post” scenario, meaning the key scenarios of interest are identified as a result of the analysis, rather than being defined prior to the analysis (so-called “a priori” scenarios). The ex post scenarios serve as the basis for risk assessment (assigning levels of concern or priority to the vulnerability) and adaptation planning. They are identified using data mining algorithms such as the Patient Rule Induction Method (PRIM).

The stress testing algorithm is a computational engine that links the individual modeling tools that are used to represent and simulate the water system performance. For SFPUC, this includes hydrologic models of the watersheds that produce reservoir inflows, water resources models or “system” models that represent reservoir storage, operations, infrastructure linkages, demand, and revenue generation and a climate/weather generator, which is a stochastic model that generates time series of inputs for the hydrologic models that simulate a wide range of climate changes. The systems model will also be extended to include other key uncertain factors, such as social, technical, economic and other changes. The potential need to include water quality modeling will also be considered.

The final step is to assign the relative level of concern to the vulnerabilities that are identified, which is associated with judgment of how likely they are and can serve to assist prioritization of actions. The estimation of level of concern typically depends on the judgment of experts and incorporation of quantitative estimates when appropriate, such as those used to derive probabilities from ensembles of GCM projections. These estimated risks will serve as a starting point for risk assessment and adaptation planning conducted in the next Phase of this project.
Climate Informed Estimation of Hydrologic Extremes for Robust Adaptation to Non-Stationary Climate

Overview

The purpose of this project is to develop and evaluate methods to produce the next generation of intensity-duration-frequency curves for engineering design at United States Department of Defense installations. More simply, this project aims to develop new methods based on large scale climate patterns to project extreme rainfall and flood events, and then determine how those projections can be used in engineering design.

This project is funded by the Strategic Environmental Research and Development Program within the United States Department of Defense and is being performed in collaboration with Columbia University and the National Center for Atmospheric Research. Within the Hydrosystems group, the primary researchers on this project are Baptiste Francois (postdoctoral researcher) and Katherine Schlef (Ph.D. candidate), with help from Sungwook Wi (postdoctoral researcher) and Jacob Kravits (undergraduate summer research assistant).

Within the last year, there have been four main avenues of research by the Hydrosystems group: (1) a review of methods for engineering design of flood mitigation strategies under non-stationarity; (2) development of various hydrological models for the catchments in the Upper Missouri River basin; (3) development of long-term projections of flood events in the Ohio River Basin using large-scale climate patterns; and (4) a comparison of different methods of choosing the flood magnitude for levee design in Louisville, KY. Additionally, the Hydrosystems Group hosted a two-day meeting with project collaborators in November 2016 at UMass, and members of the group presented results at the 2016 Fall Meeting of the American Geophysical Meeting in San Francisco and at the 2017 Northeast Graduate Student Water Symposium at UMass.
Research Avenue 1: A review of methods for engineering design of flood mitigation strategies under non-stationarity

For decades, design for hydrologic extremes has played an important role in the development of the hydrological sciences. Today, while the scientific literature discusses the emergence of factors leading to non-stationarity in hydrologic extremes, methods for designing real-world infrastructure for water resources management (e.g., dams and levees) still maintain the assumption of stationarity. The aim of this study is to discuss the different options that are currently available for assessing the value of the design flood in a nonstationary world. We first review the main sources of non-stationarity in time series of hydrological extremes. We then present the different methods for estimating the design flood in the context of climate change, one of the major sources of non-stationarity. This review reveals the gap between the available methods and real-world design guidelines. We then highlight that the notion of uncertainty in only poorly represented and discuss the advantages and drawbacks of new methods that could bridge this gap.

Annual peak flow for the Red River at Fargo, North Dakota. A significant increasing trend (i.e., non-stationarity) is observed in the latter portion of the record.

Research Avenue 2: Development of various hydrological models for the catchments in the Upper Missouri River basin

There has been growing interest for hydrologists and water resources managers about the emergence of non-stationarities associated with the hydro-meteorological processes driving floods. In particular, climate change is a key potential cause of non-stationarity, climate change. Understanding the effects of climate change on hydrological regimes of the Missouri River is challenging. In this region, floods are mainly triggered by snow melting, either when temperatures get mild in spring and summer, or when rain falls over snow in early spring and fall. The sparsely gauged and topographically complex area degrades the value of hydrological modeling that otherwise might foreshadow the evolution of hydro-meteorological interactions between precipitation, temperature and snow.
In this work, we explore the utility of deep learning for assessing flood magnitude change under climate change. By using multiple hidden layers within artificial neural networks (ANNs), deep learning allows modeling complex interactions between inputs (i.e., precipitation, temperature and snow water equivalent) and outputs (i.e., water discharge). The objective is to develop a parsimonious model of the flood processes that maintain the contribution of nonstationary factors and their potential evolution under climate change, while reducing extraneous factors not central to flood generation. By comparing ANN’s performance with outputs from two hydrological models of differing complexity (i.e. VIC, SAC-SMA), we evaluate the modeling capability of ANNs for three snow-dominated catchments that represent different flood regimes.

**Research Avenue 3: Development of long-term projections of flood events in the Ohio River Basin using large-scale climate patterns**

Estimating future hydrologic flood risk under non-stationary climate is a key challenge to the design of long-term water resources infrastructure and flood management strategies. In this work, we demonstrate how projections of large-scale climate patterns can be credibly used to create projections of long-term flood risk. Our study area is the northwest region of the Ohio River Basin in the United States Midwest. In the region, three major teleconnections have been previously demonstrated to affect synoptic patterns that influence extreme precipitation and streamflow: the El Nino Southern Oscillation, the Pacific North American pattern, and the Pacific Decadal Oscillation. These teleconnections are strongest during the winter season.

*Observed data, fitted statistical models, and projections for an example gage in the Ohio River Basin. GCM refers to general circulation model, MMM refers to multi-model mean (that is, an average of the projections), rcp 8.5 refers to the most extreme scenario of future greenhouse gas emissions, M0 and M1 refer to stationary and nonstationary statistical models, respectively, and CIs refer to confidence intervals.*
(January-March), which also experiences the greatest number of peak flow events. For this reason, flood events are defined as the maximum daily streamflow to occur in the winter season. For each gage in the region, the location parameter of a log Pearson type 3 distribution is conditioned on the first principal component of the three teleconnections to create a statistical model of flood events. Future projections of flood risk are created by forcing the statistical model with projections of the teleconnections from general circulation models selected for skill. We compare the results of our method to the results of two other methods: the traditional model chain (i.e., general circulation model projections to downscaling method to hydrologic model to flood frequency analysis) and that of using the historic trend. We also discuss the potential for developing credible projections of flood events for the continental United States.

**Research Avenue 4: A comparison of different methods of choosing the flood magnitude for levee design in Louisville, KY**

As flood risk in cities increases due to changes in climate and land-use, flood mitigation options are needed to limit future damages. However, analysis regarding the optimum design flood, i.e. the flood magnitude that a mitigation option protects against, require choices on behalf of the analyst. This work compares the modeling options of using probability-only versus risk-based analyses and assuming stationary versus nonstationary flood probabilities. As a case study, we evaluate levees in
the historically flood-prone city of Louisville, Kentucky. For probability-only analysis, the optimum design flood is the 100-year flood. For risk-based analysis, the optimum design flood is selected based on minimization of total expected cost, defined as the sum of expected damages and mitigation cost for the corresponding levee size. Damages associated with each levee were determined via Hazard US (HAZUS). HAZUS is a GIS-based software developed by the Federal Emergency Management Agency that calculates flood damages based on topographic data, flood magnitude data, and damage curves. Levee cost was estimated utilizing a calibrated function of the averaged levee height. Stationary flood probabilities were based on the historic record while nonstationary flood projections were created based on a relationship to large-scale climate patterns. Based on the results of the case study, we recommend a risk-based nonstationary analysis as extreme climate projections change both total expected cost and design flood, while a risk-based analysis guarantees a minimization of total expected cost and a justification of a design flood. This comparison is generalizable to other flood mitigation options and enables more informed investments that improve safety while reducing costs associated with over or under preparation.
Tanzania’s water resources are facing challenges as the country undergoes rapid change. The East African country’s population is expected to double by 2035 and changing lifestyles and evolving water consumption patterns are adding extra stress to this limited resource. Competing sectoral water demands and uncoordinated future economic development plans in each basin will intensify Tanzania’s water resources challenges.

Investments in water resources can help Tanzania realize its growth potential if the investments are appropriate and focused. Currently several basins in Tanzania have Integrated Water Resources Management plans, however, these plans are a laundry list of investments that requires prioritization to be effectively realized. With rapidly evolving demands for water across multiple sectors, this coordinated approach will be crucial for Tanzania to realize its development plans. Through the implementation of the *Freshwater Resilience by Design* methodology, the Hydrosystems Research Group, World Bank and Government of Tanzania will collaborate to produce a prioritized plan of investments in the Rufiji, Wami-Ruvu and Pangani basins.

Funding for this project comes from the Rockefeller Foundation.
Summary

The Hydrosystems Research Group is partnering with the World Bank and the Government of Tanzania to implement the water resources investment prioritization methodology *Freshwater Resilience by Design*. The methodology is a systematic process for evaluating and ranking investments singularly and in combination while accounting for future climate variability and change and other deep uncertainties that affect the performance of investments in the water resources sector. The result is an investment road map for achieving water-related development goals that is resilient to the uncertainties and surprises of the future.

The methodology was developed to provide technical expertise in support of the ongoing joint Rockefeller Foundation and World Bank freshwater resilience partnership. Implementation of this methodology is part of continued engagements by the World Bank in Tanzania to strengthen institutions, prioritize lines of support and identify investment needs in the water resources sector. Implementing this approach in three basins in Tanzania will build on the existing World Bank Integrated Water Resources Management work in Tanzania. The methodology will be implemented by the Hydrosystems Research Group in three river basins (Rufiji, Wami-Ruvu and Pangani) in close collaboration with the World Bank and the Government of Tanzania.

The *Freshwater Resilience by Design* methodology utilizes a systematic process for evaluating and ranking investments singularly and in combination while accounting for future climate variability and change and other deep uncertainties that affect the performance of investments in the water resources sector. The process adopts a bottom up approach to risk assessment that aims to thoroughly understand the basin’s vulnerabilities to climate change in the context of other non-climate uncertainties (for example, economic, environmental, demographic, or political). The methodology promotes freshwater resilience as a lens through which water resources investment prioritization is analyzed.

A resilient river basin is one where communities within a basin have options and use them to manage change, both sudden and gradual, while not undermining the long term ability of the basin to thrive. The analysis helps to identify investment combinations that perform well across a wide range of potential future climate conditions, as opposed to seeking solutions that are optimal in expected conditions but fragile to conditions deviating from the expected. The result is an investment road map for achieving water-related development goals that is resilient to the uncertainties and surprises of the future.
Tanzania - Freshwater Resilience by Design

Basin Descriptions

The Rufiji basin is characterized by competing water demands from several sectors, with agriculture, hydropower and flows for the environment vying for the same scarce resource. Challenges are acute during dry season and the effects on flow in dry years are worsening as uncoordinated agriculture expansion increases in the basin (see Box 1). National Parks and Game Reserves occupy a large portion of the basin, and increases in irrigated agriculture area through a government funded initiative (SAGCOT) will place further stress on water resources. Continued uncoordinated irrigation expansion, future hydropower development and will lead to reduced environmental flows, jeopardizing protected parks and reserves and the dependent tourism economy.

Box 1 - Ruaha National Park in the Rufiji basin during the dry season

Our convoy of Land Cruisers drove down the washboard dirt road as we passed villages and small children and adults carrying buckets of water balanced precariously on their heads. As we got further away from the paved road and relative comfort of the small town of Iringa, the settlements got smaller and smaller. Along the narrow one lane road, our vehicles kicked up so much of the dry soil that we followed a cloud of dust in front of us – not even a discernable outline of the Land Cruiser was visible. We passed thousands of leaf-less trees and shrubs that looked thirsty for water. After over a hundred kilometers of this journey, we arrived at the gate to Ruaha National Park, one of the ecological gems of the Rufiji Basin in southern Tanzania. This is a vital ecosystem for megafauna (elephants, giraffes, lions, antelope, hippos) and a major tourist destination. Another 20 kilometers onward, we arrived at the Great Ruaha River. Had we not passed a sign and crossed a bridge, we may have completely missed the river. There was zero flow.

The dry season in Tanzania lasts for months, and our trip to the Great Ruaha River in late September occurred during one of the driest times of the year. The dry season, however, did not always mean zero flow in the Great Ruaha. Hundreds of kilometers upstream, thousands of liters of water are abstracted from the Great Ruaha before it enters the park. Most of the water is diverted from the river to feed thirsty crops in both large scale formal and smaller informal farms. The water used for increasing agriculture upstream has diminished the flow through the National Park and increased the prevalence of zero flow days in recent decades. Hundreds of kilometers downstream of the park, two hydropower reservoirs (Mtera and Kidatu) are operating at far below their peak capacities. The ring of exposed land around the Mtera reservoir grows larger and larger as less water flows from upstream to fill the large body of water – the largest in the Rufiji basin.

As the trees, megafauna, farmers, and the empty reservoirs await the onset of the rainy season, many wonder how this limited resource can be shared, especially during the dry season. As we stood along the banks of the great floodplain and looked at a few small pools below, we could see this competition taking shape amongst the park’s fauna. A herd of elephants was drinking and playing in a pool where each animal had to squeeze to gain access to the small supply of water. Hippos were crowded into a pool with crocodiles just to try and stay submerged under the hot African sun. Zebras, gazelles, and giraffes traveled the banks looking for a suitable pool to stop for a drink. A lazy lion perched at a high point along the bank monitored the scene.

It’s hard to imagine that in the rainy season, the torrent of water passing in the space before us could over top the banks several meters above the flat floodplain. During this time, there is plenty of water to go around, but in these driest times of year, allocating water to various different demands has becoming increasingly difficult.
The **Wami-Ruvu basin** contains the urban centers of Dar es Salaam, Morogoro and Dodoma, the capital city. These rapidly growing urban areas demand more water each year, and there are already plans for expanded irrigation and industry in the basin. **Expanded industrial activities are planned in the basin, particularly in the corridor between Dar es Salaam and Morogoro, further stressing the water resources in this area of the basin.**

The **Pangani basin** is the most water stressed catchment in Tanzania. With expanding water abstractions projected for urban and industrial centers, existing hydropower and irrigation requirements and flows for the natural environment, coordination is needed to account and allocate water in the basin.
Implementation

Rolling out the Freshwater Resilience by Design methodology in Tanzania will require a strong partnership between the HRG, World Bank and Government of Tanzania. The HRG began this engagement in September 2017 and it is expected to continue through September 2018. The following steps outline the process and timeline for applying the methodology to the Rufiji, Wami-Ruvu and Pangani basins in Tanzania.

1. **Define Resilience and Scope of Analysis** – This process will begin with an initial inception workshop that convenes stakeholders, establishes relationships, and defines metrics for success in each basin. This meeting will set the scope of the analysis and define the investment prioritization objective.

2. **Collaborative Modeling** – The HRG will work with the World Bank and Government of Tanzania to develop a coupled hydrologic and systems model of each basin. The details of the modeling will be completed collaboratively by the HRG and a technical team within the government identified within each basin. The model will represent the physical features of the basin and highlight key nodes where further analysis can take place. The models will be calibrated and validated over a period of record to be determined, based on available streamflow and precipitation data. The models will be modifiable to test various investment scenarios for prioritization.

3. **Data Analytics Discovers Optimal Resilience Investment Portfolios** – The collaborative team conducts the multi-criteria, multi-scenario options analysis optimization. The team will run hydrologic and systems models through a stress test to determine the optimal investment combination to achieve the goals defined in the first phase. The metrics used in the analysis align with the specific interests of stakeholders across sectors defined during the inception meeting.

   During the stress test, future climate predictions for precipitation and temperature are considered based on the range of global circulation model projections. Various development patterns are considered, and different combinations of sectoral demands are analyzed. These basis for these combinations are defined during the initial inception meeting and will depend on demographic trends and demands within each basin. All arrangements of individual investments and combinations of investments are added and tested through these future climate and development scenarios to uncover the optimal investments to achieve the objectives defined in Phase I.

4. **Design a Water Security and Resilience Implementation Plan** – The HRG and partners will design a water security and resilience plan and implementation timeline that highlights optimal investment design. The robustness and resilience of the investment plans will be elucidated and the success of the investment combination will be based on the specific metrics and scope of work defined in Step 1.
Results of the investment prioritization analysis will be presented to the World Bank, Government of Tanzania and other interested parties. The results will be presented to ensure that the process fits within the existing institutional frameworks and processes already in place at these organizations.

The results will be summarized in a final report on the investment prioritization plan. The investment prioritization analysis will comprise an investment strategy plan for the river basins undergoing this analysis. This plan will include a portfolio of prioritized investments and an implementation timeline.

The HRG will also lead a training workshop for the Government of Tanzania and local learning centers including the Water Resources Management Institute and the University of Dar es Salaam (Water Resources Department) to train local partners and ensure they are capable of executing the Freshwater Resilience by Design process to add to their capacity to develop this framework in other settings.

The project is ongoing and is expected to be completed by September 2018.
Personnel

Hydrosystems Research Group

From Left to Right: Casey Brown, Januka Gyawali, Sarah Freeman, Dong Kwan (Don) Park, Chinedum Eluwa, David Rheinheimer, Khan Nguyen, M. Umit Taner, Hassaan Khan, Sungwook Wi, Baptiste Francois, Katherine Schlef, Alec Bernstein, Mariam Allam
Mariam Allam

Mariam Allam is a postdoctoral research associate who started working with the Hydrosystems Group in 2017. She recently graduated with a PhD from the Civil and Environmental Engineering department at MIT during which she studied the food-water-energy nexus in the upper Blue Nile basin and found alternatives for win-win opportunities for the three stakeholder countries sharing the basin’s water. Mariam did her MSc and BSc in Cairo University in water resources engineering. When she is not thinking about resource allocation problems, Mariam is a fitness maniac! She is a certified group exercise instructor and a BollyX instructor and she enjoys long runs!

Alec Bernstein

Alec Bernstein is the Hydrosystems Group Project Manager and began work with the Group in 2016. Alec previously worked as a water resources engineer in Seattle, WA, and also worked briefly at a startup on water distribution system monitoring hardware. From 2013 to 2014, Alec conducted independent research in India as a Fulbright-Nehru Scholar investigating water treatment system sustainability in communities in rural West Bengal. Alec completed his M.S. from the University of Massachusetts in civil engineering with a focus in water resources engineering in 2013, and a B.S. from Lafayette College in civil engineering in 2011. He enjoys collaborating with local stakeholders to solve complex water resources challenges, and has worked on projects in Latin America, Asia, Africa, and North America. Alec has a passion for the outdoors and enjoys biking, hiking, camping, cooking, brewing, playing and listening to music, and any water-related activities from a lazy day at the beach to hiking on glaciers.

Chinedum Eluwa

Chinedum Eluwa started work as a Research Assistant in the Hydrosystems Research Group in September 2016 when he moved to Amherst, MA to begin a PhD in Water Resources Systems Analysis. Prior to this he completed a Master’s degree in Hydrology and Climate Change (in Newcastle, UK) and worked as a researcher to develop flood risk assessment methods for the European Union RAMSES climate adaptation project. In his current work, he helps governments (including inter-governmental organizations) decide which water-resources infrastructure investment options to pursue given future uncertainties – especially hydro-climatologic uncertainties. When not working, Chinedum enjoys listening to economic or political debates on one of the BBC’s channels.
Sarah Freeman
Sarah Freeman is a PhD student in the Hydrosystems Research Group. Ms. Freeman joined the group in the fall of 2016 after spending the past decade working for both private sector and non-profit organizations in the infrastructure and environmental conservation sectors. She has worked in a variety of roles that have included project management, scientific research as well extensive work with stakeholder processes around the world. She is particularly passionate about how science can inform policy. Ms. Freeman is currently leading the HRG’s Resilience by Design project in the Valley of Mexico. She was recognized as the 2009 American Council of Engineering Companies (ACEC) Young Professional of the Year and holds a MSc in Water Resources Engineering and her BS in Mechanical Engineering from Tufts University. She is also the designated cocktail maker for the HRG and occasionally a soccer co-captain along with Katherine Schlef.

Baptiste François
Dr. Baptiste François is a postdoctoral researcher in the Hydrosystems Research Group at the University of Massachusetts, Amherst. He has a PhD in hydrology and atmospheric sciences from the University of Grenoble-Alpes (France). His research focuses on the water-climate-energy nexus. He is especially interested in the impact of climate change on the integration of intermittent renewable energy sources into the future electricity grid. His postdoctoral research led him to work at the University of Padua (Italy, 1 year), at the SINTEF Energies research institute (Trondheim, Norway, 9 months) and at the University of Grenoble-Alpes, where he got his PhD (2 years). He is now working on assessing climate change impacts on hydrological extremes.

Januka Gyawali
Januka Gyawali is a Fulbright Scholar in a graduate program of Civil and Environmental engineering at University of Massachusetts Amherst. She holds both of her B.E. in Civil Engineering and M.Sc in Water Resources Engineering from Institute of Engineering, Pulchowk Campus, Nepal. Prior to joining UMass Amherst, she worked as a civil engineer in Nepal Electricity Authority. She likes to listen music, read novels, hike and travel during her free time.
Hassaan Khan

Hassaan Khan is a doctoral candidate in the Hydrosystems Research Group and joined the group in 2013. Like many others in the group, he has been involved in a variety of interdisciplinary projects throughout his graduate career. For his dissertation, he is evaluating the use of coupled natural and human systems for water resources planning in water scarce regions around the world. Hassaan obtained his M.S in Environmental Engineering from the University of Massachusetts in 2016, and a B.S. in Civil and Environmental Engineering from Lafayette College. Hassaan is originally from Karachi, Pakistan, a mega city with major water challenges. He enjoys learning about and experiencing different cultures through traveling. In his free time, he likes to cook, watch soccer, and read about history and religion, with a special interest in the Middle East and South Asia.

Khanh Nguyen

In 2013, Khanh Nguyen obtained a Bachelor of Engineering in environmental management and technology at Ho Chi Minh City University of Technology (HCMUT), Vietnam. After graduation, Khanh worked as Research Assistant in the domain of Geographic Information System and hydrological modeling at DITAGIS center, HCMUT. In 2014, she worked as Corporate Environmental Coordinator in Holcim Vietnam Ltd., where she undertook tasks of CO2 reporting and waste management. Six months later, Khanh began her masters program in environmental science and engineering with the expertise of hydrology, water, soil and ecosystems at Swiss Federal Institute of Technology (EPFL), Lausanne, Switzerland under a RESCIF-CARE fellowship. During the masters program, she worked as an intern at GeoplanTeam which is a Swiss enterprise in geo-informatics and geographic information systems. In 2017, Khanh achieved her masters degree and became a graduate student in the Hydrosystems Research Group at University of Massachusetts Amherst.

Dong Kwan (Don) Park

Dong Kwan (Don) Park is a first year Ph.D. student with the Hydrosystems Research Group from Fort Collins, Colorado. He completed his B.S. in 2013 from The Pennsylvania State University in Civil Engineering – Water Resources and received his M.S. from Seoul National University in 2015 in Civil Engineering with a focus in Hydrology and Water Resources. From 2014 through early 2017, Don worked at Seoul National University as a researcher developing an integrated framework that includes social, environmental, and water resources through the Model of Integrated Impact and Vulnerability Evaluation of climate change (MOTIVE) project with the Ministry of Environment Korea. In his free time, Don enjoys camping, hiking, cooking, and listening to music.
**Personnel**

**David Rheinheimer**

Dr. David Rheinheimer is currently a Postdoctoral researcher in the Hydrosystems Research Group. With a PhD from the University of California, Davis, his interests are primarily in environmental flows, which encompasses seeking a better understanding of how environmental flows can be better represented in water systems models and how environmental flow requirements interact with other water management objectives and changing baseline conditions. David has recently turned to web technologies, which enable both easy access to on-demand cloud computing and rapid development of collaboration platforms for distributed participatory modeling and decision-making. David has a wide range of previous experience in the Federal Government (the U.S. Department of Energy and the National Oceanic and Atmospheric Administration) and in academia. He has been a Postdoc at the University of California (Davis & Merced campuses), Wuhan University, China, and at the Indian Institute of Technology, Roorkee as a Fulbright-Nehru Postdoctoral Fellow. Before coming to UMass, he was a Research Specialist at the Tecnológico de Monterrey in Monterrey, Mexico. An avid outdoorsman, David enjoys walking, hiking, backpacking, biking and sailing, and has climbed many a local peak wherever his travels take him. He is also an avid amateur photographer and clarinetist.

**Katherine Schlef**

Katherine Schlef will complete her Ph.D. in May 2018 in civil engineering with a focus on water resources from the University of Massachusetts Amherst. She received a M.S. in civil engineering from the same institution in 2014 and a B.S. in general engineering from Harvey Mudd College in 2012. Katherine spent the 2014-2015 school year in Burkina Faso with the Fulbright U.S. student program studying urban flood risk assessment and management. She was awarded a National Science Foundation Graduate Research Fellowship in 2012. She has a passion for understanding the complex interactions between water, humans, and the environment.

**M. Ümit Taner**

Dr. M. Ümit Taner, is a postdoctoral researcher at the University of Massachusetts, Amherst. He received his PhD from the University of Massachusetts, Amherst in 2017. He has more than ten years of experience in international water projects, ecological modeling, and wastewater treatment. Previous to University of Massachusetts, he had worked at the Scientific and Technological Research Council of Turkey (TUBITAK-MRC) and at the U.S. Environmental Protection Agency (US EPA), Office of Water. During his Ph.D. work, he developed various hydrology and water resources system models and web-based tools to aid long-term water systems planning under climate change. He has also instructed a number of stakeholder workshops in Africa and Asia for various World Bank funded projects. His recent work includes various water system planning and management projects in United States, Kenya, Malawi, and the Niger River Basin. Currently, his work focuses on integration of vulnerability-based planning...
approaches and robust optimization to solve complex planning problems involving long-term water, food, and energy security.

**Sungwook Wi**

Dr. Sungwook Wi is a postdoctoral research associate in the Department of Civil and Environmental Engineering at the University of Massachusetts (UMASS) Amherst and a chief hydrologist at the UMASS Hydrosystems Research Group. His research focuses on the intersection between hydrologic, climatic, and anthropogenic systems with an emphasis on sustainable water resources management. He specializes in developing human-hydrologic systems models and applying the models to assess the impact of climate change and variability as well as human activities on water resources planning and management. His expertise in hydrology has played a critical role in addressing water issues for various watershed systems all over the world, including USA, Mexico, Africa, East Asia, and Himalayan regions.
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